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An extended data set of river discharges for validation of general circulation models

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Abstract. Using existing measurements of streamflow data, we present a new data set of river discharges to the ocean, for use in validating climate models. This data set includes annual mean discharges for 981 rivers, representing approximately 824,500 m^3/s of global river discharge. This is about 65% of contemporary estimates of continental precipitation minus continental evaporation (*P-E*). Using our new data set, we present a self-consistent water budget over continents. We find that rivers with annual mean discharges between about 250 m^3/s and about 20,000 m^3/s closely follow a power law size distribution. We estimate the total flow from rivers smaller than 250 m^3/s by assuming they obey the same power law size distribution. Under this assumption, the estimated total flow from these rivers is about 33% of *P-E*. Including an existing estimate of soil moisture entering the ocean underground, our estimated total flow into the ocean is within about 2% of contemporary estimates of continental *P-E*. Our data set is available in digital format.

1. Introduction

The large-scale transport of water is an important aspect of the climate system. The transport of water is closely tied to a redistribution of energy, through the processes of precipitation, evapotranspiration, and condensation. The net flux of fresh water into the oceans affects the ocean thermohaline circulation. Land-surface hydrology partially controls the rates of growth and decomposition of most vegetation species, and hence affects the global carbon cycle.

Despite its importance, large-scale hydrology is typically treated with less sophistication than other aspects of global climate models. One reason for this is that validation of large-scale land-surface hydrologic calculations is difficult. Most of the physical processes being modeled (evapotranspiration, soil moisture content, surface runoff, etc.) are extremely heterogeneous, and hence are difficult to measure on the large scale; thus, it is difficult to determine if model calculations agree with the observed hydrologic properties.

The hydrologic cycle in climate models can be validated in part by using observed river discharge data. Computed continental river discharge can be compared to measurements of river discharge at gauge stations near significant river outlets. If the simulated flows agree closely with the observed river discharges, then confidence in the simulated hydrologic system is increased.

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[2]Supporting data [tables, calculations, appendices, etc.] are available on diskette or via Anonymous FTP from kosmos.agu.org, directory APEND (Username = anonymous, Password = guest). Diskette may be ordered from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009 or by phone at 800-966-2481; $15.00. Payment must accompany order.

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A pair of data sets have been compiled specifically for the validation of climate model output [*Dumenil et al.*, 1993; *Russell and Miller*, 1994]. However, these data sets include only 46 and 33 rivers, respectively, which represents approximately 462,000 m^3/s and 557,000 m^3/s of total global river discharge. Thus these data sets are of limited utility for general circulation model (GCM) validation. A more extensive existing river flow data set is that of *UNESCO* [1985]. In recognition of the need for a more complete, systematically prepared data set, we developed the data set described here. The full data set is available electronically.[2]

The following section of this paper discusses the sources of data and the methods that were used to compile our river flow data set. Section 3 describes some of the statistical characteristics of this data set. In section 4 we estimate the flow in small rivers missing from our data set, and compare estimates of river flow to estimates of flow from continents obtained by subtracting estimated evaporation from estimated precipitation over continents. Section 5 gives our conclusions.

2. Construction of Our Data Set

Sources of Data and Compilation Procedure

We provide a data set of observed river discharges by analyzing and selectively combining existing published observations. Approximately 49 sources of data (listed in the appendix) and over 1950 separate quoted values were used to compile our data set. A number of these sources do not appear to have been referenced in previous global river discharge data sets.

While the largest rivers are of primary interest, we attempted to include in our data set all rivers that have a recorded streamflow. As discussed below, this procedure resulted in multiple usable flow rate measurements for many of the rivers in out data set. Figure 1 (in conjunction with the appendix) shows which sources contributed flow rates for the largest rivers in our data set. In a few cases, a river had a significant tributary downstream from the final gaging

River Number

Source Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
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Note: Sources that do not provide values for any of the rivers shown in this table were omitted.

Figure 1. A matrix indicating which sources contributed measured flow rates for the largest rivers in the data set. The left axis lists data sources by number (see appendix for corresponding numbered references); the top axis lists the rivers by number (see Table 2 for corresponding numbered river names and locations). Also, a + indicates that the source on the left axis contributed a flow measurement for the river indicated on the top axis.

station. To include the flow from these tributaries, they were listed separately in the data set, with the same mouth as the main river.

Despite a strong effort to identify the location of all of the rivers for which data was available, we identified 89 rivers with a total recorded outflow of 3,968 m^3/s which could not be located geographically and therefore could not be included in our data set. Probably some of these rivers are tributaries of larger rivers already in our data set and thus would not have been included anyway.

Error Estimation, Averaging, and Elimination of Outliers

Table 1, which lists all available flow rate measurements for three large rivers (Amazon, Zaire, and Irrawaddy), shows that discrepancies between different reported discharge values for the same river can be significant. These discrepancies arise because of measurement errors, seasonal, and interannual variability in river discharges, human activities (e.g., dam construction) which change river flow rates, and the fact (discussed below) that different measurements can be made at different locations on the river, some of which are significantly upstream from the river mouth. The differences between individual measurements of the same river can be extreme, as much as an order of magnitude in a few cases. At the same time, Table 1 also shows that different sources often report identical flow rates for the same river. Given the large discrepancies discussed above between independent measurements, it seems likely that sources reporting identical flow rates for the same river are quoting the same primary source (i.e., that there is only one independent measurement among them). In light of these two issues (large discrepancies between independent measurements and multiple reports of the same measurement), we adopt the following procedure for calculating means and standard deviations of flow rates for each river in our data set. (1) All available flow rate measurements are used, except when the location of the river could not be determined, when another measurement, made further downstream, was available for the same river or when the river drains to an internal basin (e.g., the Aral Sea). (2) For each river, if more than one source quotes the same flow rate, all but one of these is eliminated. As discussed above, this is done on the presumption that identical reported flow rates are more likely to result from multiple sources quoting the same measurement than from independent measurements which produce exactly the same flow rate. (3) The mean and standard deviation of remaining flow rates is calculated. (4) Flow rates more than two standard deviations from the mean are eliminated. (5) The mean and standard deviation of remaining flow rates are calculated. These are the final values used in our data set.

Flow rates determined by this procedure are shown for the largest rivers in our data set in Table 2. The standard deviations in our data set provide some indication of the uncertainty in the reported flow rates. For rivers with more than one flow measurement, the standard deviation of the included values is typically 10 - 20% of the mean, irrespective of the size of the river; examples are shown in Table 2. Because of possible systematic errors (particularly errors due to upstream location of flow measurements, discussed below), actual uncertainties are generally higher than these values.

For our purposes, determining fresh water fluxes to the ocean, river flow should ideally be reported at the mouth of each river as it discharges into the ocean. However, most river

Table 1. River Flow Values from All Sources for Selected Rivers.

River	Flow (m^3/s)	Source
Amazon	212400	*van der Leeden et al.* [1991]
	212000	*Szestay* [1982]
	200000	*Kammerer* [1989b]
	199800	*Milliman and Meade* [1983]
	198600	*Probst and Sigha* [1989]
	196600	*Meybeck* [1993]
	190000	*Baumgartner and Reichel* [1975]
	183300	*Degens et al.* [1991]
	180000	*Czaya* [1981]
	175000	*Spitzy and Leenheer* [1991]
	175000	*Meybeck* [1988]
	175000	*Showers* [1979]
	174400	*Depetris and Paolini* [1991]
	174400	*Degens et al.* [1991]
Zaire	46000	*Esser and Kohlmaier* [1992]
	44000	*Kammerer* [1989b]
	42000	*Czaya* [1981]
	42000	*Baumgartner and Reichel* [1975]
	41200	*Degens et al.* [1992]
	41100	*Nkounkou and Probst* [1987]
	41100	*Probst and Tardy* [1987]
	41100	*UNESCO* [1985]
	40700	*Probst and Sigha* [1989]
	40000	*Szestay* [1982]
	39600	*van der Leeden et al.* [1991]
	39600	*Milliman and Meade* [1983]
	39600	*Leopold* [1962]
	39200	*Spitzy and Leenheer* [1992]
	39200	*Meybeck* [1988]
	39200	*van der Leeden* [1975]
	39000	*Showers* [1979]
Irrawaddy	14000	*Kammerer* [1989b]
	14000	*Czaya* [1981]
	14000	*Baumgartner and Reichel* [1975]
	13600	*Degens et al.* [1992]
	13600	*Subramanian and Ittekkot* [1991]
	13600	*van der Leeden et al.* [1991]
	13600	*Milliman and Meade* [1983]
	13600	*Szestay* [1982]
	13600	*Leopold* [1962]
	13400	*Meybeck* [1988]
	12700	*Showers* [1979]

gauges are located well upstream of the ocean. (Examples are provided in Table 3.) As discussed above, when measurement locations were available, we used measurements made as close as possible to the ocean. In most of our sources, however, the exact location of the measurements are not reported. Thus in many cases, the flows reported here were measured a significant, and unknown, distance from the ocean. These upstream flows are generally, but not always, lower than the flows at the river mouth. In a few instances, such as the Nile and Colorado rivers, the flow diminishes downstream due to evaporation or infiltration as it flows through a desert area or is diverted for irrigation.

Other quantities that may have some error are the quoted longitude and latitude of the river mouths. In most cases, this was determined by checking the location (Rand McNally's *The New International Atlas*). Latitudes and longitudes should be well within 0.5 degrees of the true location, which is adequate for validation of global climate models.

3. Characteristics of the Data Set

As discussed in detail below, we believe that our data set is very incomplete for rivers with flow rates less than 250 m^3/s. Even for larger rivers however, our data set is more complete in some locations than in others. In general, small rivers are much more likely to be reported in countries with dry desert climates, such as North Africa, or on small islands. Similarly, small rivers that flow through important agricultural or urban areas are more likely to be reported than small rivers that flow through remote areas. In particular, we found little or no river discharge data, for Indonesia (except Java), Malaysia, parts of the Arctic and parts of South America. In the case of Indonesia, we found no reported data for the islands of Sumatra, Borneo, Celebes, or the western half of New Guinea, despite the fact that these islands are located near the equator, are mountainous, and thus should have significant precipitation and river discharge. (Papua New Guinea, the eastern half of New Guinea, contains three of the 50 largest rivers in our data set.) There is also no data for the Malaysian part of Borneo. Brazil appears to have a few medium-sized unreported rivers. Russia, Canada, and Alaska have data for many of the rivers that drain into the Arctic Ocean, but others are unrecorded.

The fact that our data set is less complete for Oceania than elsewhere can be seen in Figure 2. Here we show for each continent the total flow from all rivers in our data set compared to an estimate of precipitation minus evaporation (*P-E*) from *Baumgartner and Reichel* [1975]. For all continents except Oceania, the total discharge in our data set amounts to 60 - 70% of *P-E*. (As discussed below, most of the remaining 30 - 40% may be in small, unrecorded rivers.) For Oceania, however, our data set includes only 23% of Baumgartner and Reichel's estimated *P-E*. This is consistent with the above discussion suggesting that our data set is relatively incomplete in that region.

Figure 3 shows the total discharge as a function of the number of rivers included from our data set. Roughly 50% of the total discharge in the data set is from the 10 largest rivers, 75% is in the first 51 rivers, 90% is in the largest 186 rivers and 98% is contained in the 459 largest rivers. The remaining 522 rivers in the data set contribute only 2% of the total discharge in our data set.

Figure 4 shows the global river discharge as a function of latitude. The largest discharge value is found between 0°S - 5°S, due mostly to the presence of the Amazon river in this latitude band. Total discharge values are larger in the northern hemisphere (497,545 m^3/s or 60.3%) than the southern hemisphere (326,955 m^3/s or 39.7%), partly because there is more land area in the northern hemisphere than in the southern hemisphere. The relatively high discharge values in the Arctic due to the north flowing rivers of Siberia, Europe, and North America are apparent. Plate 1 shows a world map with discharges for each river in our data set. The magnitude of the discharge is indicated by the color at the river mouth. Again, the reported discharge values tend to be too low because most rivers have been measured upstream from continental boundaries.

4. The Large-Scale Water Budget Over Continents

In this section, we estimate the flux of water to the ocean from small rivers not included in our data set. We show that this estimate, combined with an existing estimate of underground flow to the ocean and the observed discharges in our data set, closely approximates previous estimates of global river discharge obtained by subtracting estimated evaporation over continents from estimated precipitation over

Table 2. Flow Rates, Cubic Meters per Second, for Largest Rivers in Our Data Set.

Rank	River Name	Country	Latitude	Longitude	Number of Sources	Arithmetic Mean Flow	Standard Deviation
1	Amazon	Brazil	0.0	310.0	11	192918	12859
2	Zaire	Zaire	-6.0	12.5	9	40755	1483
3	Ganges/ Brahmaputra	Bangladesh	22.0	91.0	11	34000	3498
4	Orinoco	Venezuela	9.0	299.0	8	30950	3810
5	Chang Jiang (Yangtze)	China	31.5	122.0	15	28863	3576
6	Yenisei	Russia	72.0	82.0	10	18350	1001
7	Parana (Plata)	Argentina	-35.0	303.0	8	16387	1511
8	Mississippi	USA	29.0	271.0	12	16287	2082
9	Lena	Russia	73.0	127.0	8	16287	398
10	Mekong	Vietnam	10.0	106.0	8	14850	1880
11	Irrawaddy	Burma	16.0	95.0	4	13425	471
12	Ob	Russia	72.0	73.0	9	12738	557
13	Saint Lawrence	Canada	49.5	295.5	9	11458	1483
14	Tocantins	Brazil	-0.5	311.5	5	10400	1186
15	Amur	Russia	53.0	141.0	7	10185	527
16	Xi (Zhu Jiang) (Pearl)	China	22.2	113.4	8	9611	1882
17	MacKenzie	Canada	69.0	225.0	8	9013	1076
18	Columbia	USA	46.3	236.0	6	7460	455
19	Magdalena	Colombia	11.0	285.0	4	7325	465
20	Yukon	USA	63.0	195.0	10	6412	552
21	Danube	Romania	45.2	29.7	7	6365	141
22	Indus	Pakistan	24.0	67.5	7	6092	1122
23	Salween	Burma	16.5	97.0	2	5750	4250
24	Niger	Nigeria	-4.0	6.0	6	5533	575
25	Sepik	Papua New Guinea	-3.8	144.5	2	5150	1350
26	Fly	Papua New Guinea	-9.0	143.0	4	4960	2752
27	Ogooue	Gabon	-1.0	9.0	3	4686	12
28	Uruguay	Argentina	-35.0	303.8	7	4618	529
29	Bengawan Solo	Indonesia	-6.8	112.6	2	4240	3360
30	Zambezi	Mozambique	-18.7	36.5	6	4121	2093
31	Pechora	Russia	68.0	54.0	4	4052	35
32	Red (Hungho) (Sankai)	Vietnam	20.5	106.5	2	3750	150
33	Fraser	Canada	49.5	236.5	6	3590	210
34	Meghna	Bangladesh	22.5	91.0	1	3515	0
35	Severnaya Dvina	Russia	64.5	41.0	9	3418	87
36	Godavari	India	16.5	82.0	8	3250	447
37	Khatanga-Popigay	Russia	73.0	107.0	2	3240	40
38	Sao Francisco	Brazil	-10.5	323.5	11	3087	364
39	Kolyma	Russia	69.0	161.0	6	2985	740
40	Neva	Russia	59.9	30.3	7	2524	41
41	Pyasina	Russia	73.5	87.0	5	2512	135
42	Nelson	Canada	57.0	268.0	7	2495	200
43	Koksoak	Canada	58.0	292.0	3	2460	63
44	Tarum	Indonesia	-6.0	107.0	1	2400	0
45	Purari	Papua New Guinea	-8.0	145.0	3	2376	63
46	Usumacinta	Mexico	18.0	267.0	5	2339	791
47	Atrato	Colombia	8.4	283.0	1	2275	0
48	Rhine (Rhein)	Netherlands	52.0	4.0	6	2246	53
49	Essequibo	Guyana	7.0	301.5	3	2198	19

Table 2. (continued)

Rank	River Name	Country	Latitude	Longitude	Number of Sources	Arithmetic Mean Flow	Standard Deviation
50	Sanaga	Cameroon	4.0	10.0	4	2087	71
51	San Juan	Colombia	4.2	283.4	1	2010	0
52	Mahanadi	India	20.0	87.0	6	2008	158
53	Corantijn	Surinam	6.0	302.8	1	2000	0
54	Min	China	26.1	119.7	2	1905	55
55	Krishna (Kistna)	India	16.0	81.0	5	1894	185
56	Maroni (Marowijne)	Surinam	5.8	306.0	4	1877	82
57	Nile	Egypt	31.5	31.0	10	1829	787
58	Mobile	USA	30.2	272.0	4	1752	93
59	La Grande	Canada	53.8	281.0	3	1720	24
60	Saguenay	Canada	48.1	290.2	5	1701	116
61	Churchill 1	Canada	54.4	302.5	3	1686	123
62	Indigirka	Russia	71.0	150.0	7	1631	111
63	Dnieper	Ukraine	46.5	32.3	6	1630	69
64	Rhone	France	43.5	4.5	8	1630	71
65	Tanduj	Indonesia	-7.7	108.8	1	1595	0
66	Taz	Russia	67.7	78.7	1	1540	0
67	Kuskokwim	USA	60.0	162.5	5	1503	323
68	Guayas	Ecuador	-2.5	280.0	1	1490	0
69	Tsientang	China	30.2	120.3	1	1490	0
70	Po	Italy	45.0	12.5	9	1476	38
71	Shatt-al-Arab	Iraq	30.0	49.0	6	1445	284
72	Narmada	India	21.5	72.5	3	1401	232
73	Huang He (Yellow)	China	38.0	119.0	11	1361	155
74	Copper	USA	60.5	215.0	5	1344	286
75	Skeena	Canada	54.1	230.0	4	1331	413

Columns 4 and 5 give the latitude and longitude of the river mouth. Column 6 gives the number of measurements used to obtain the mean and standard deviation of the flow rate (columns 7 and 8).

Table 3. Gauging Station Distances to River Mouths for Large Rivers

River	Gauging Station Location	Distance, km
Amazon	Obidos, Brazil	750
Zaire	Kinshasa, Zaire	425
Orinoco	Ciudad Bolivar, Venezuela	325
Ganges	Paksey, Bangladesh	325
Brahmaputra	Bahadurabad, Bangladesh	375
Chang Jiang	Datong, China	525
Yenisei	Igarka, Russia	700
Mississippi	Tarbert Landing, Miss., USA	400
Lena	Kusur, Russia	300
Parana	Posadas, Argentina	1250
St. Lawrence	Cornwall, Ont., Canada	775
Ob	Salekhard, Russia	300
Amur	Komsomolsk, Russia	525
Tocantins	Itupiranga, Brazil	600
Xi	Wuzhou 3, China	375
MacKenzie	Norman Wells, N. W. T., Canada	700
Magdalena	Calamar, Colombia	100
Yukon	Kaltag, Alaska, USA	675
Niger	Jebba, Nigeria	700
Uruguay	Salto, Uruguay	425

(Distances estimated from maps)

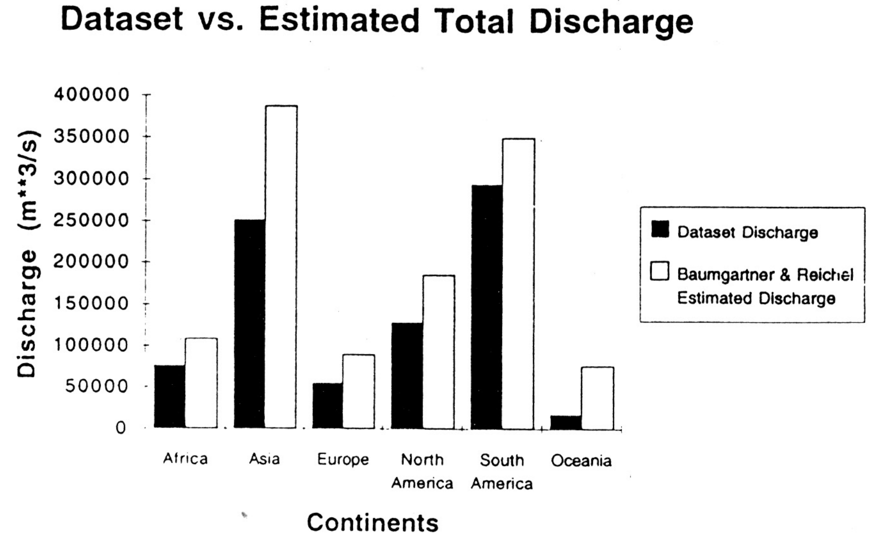

Figure 2. Fresh water flux to the ocean by continent, obtained by summing rivers in our data set (solid bars) and estimated by *Baumgartner and Reichel* [1975] by subtracting evaporation from precipitation (*P-E*). Except for Oceania, our data set fluxes are about 70% those estimated from *P-E*.

continents (*P-E*). Thus we present a self-consistent budget of fresh water over continents in the sense that our results are consistent with existing *P-E* measurements.

Previous researchers have estimated the total flow of fresh water from the continents into the ocean from the conservation law for water over continents:

$$P = E + D + R + U \tag{1}$$

where
P = precipitation
E = evaporation
D = discharge, runoff, and interflow between soil and surface
R = temporary soil storage of water
U = consumption (chemically or physically bound water)

Since the long-term (multiyear) average is of interest, it is assumed that long-term averages of R and U are zero, and (1) can be simplified to:

$$P = E + D \tag{2}$$

Using observed data, maps of the areal distribution of precipitation and evapotranspiration are prepared; in some cases, observed river flow is used to adjust the evaporation values in a particular river basin. A map of the areal distribution of D is then obtained by subtraction. From this map, a global river discharge value is computed. Table 4 lists global river discharge estimates obtained using this approach. Estimates made since 1945 range from 1,063,300 m^3/s [*Albrecht*, 1961, as cited by *Lvovich*, 1970] to 1,521,000 m^3/s [*Budyko*, 1963, as cited by *Lvovich*, 1970], with a mean

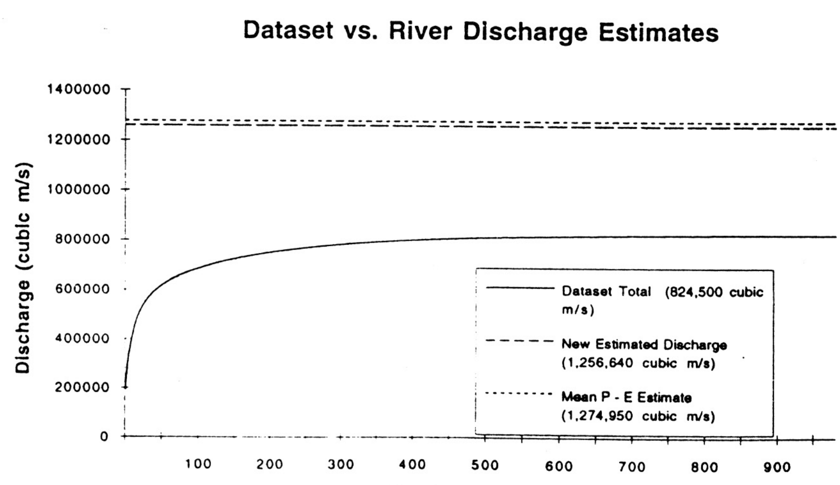

Figure 3. The volume of the global river discharge represented by the sum of the N largest rivers in the data set, as a function of N. The smallest 521 rivers contribute only 2% of the total flow in the data set. Our estimate of the total global discharge, based on our data set, an extrapolation for small rivers, and an estimate of underground discharge, is also shown. In addition, we show the mean of a number of contemporary estimates of global flow to the ocean based on continental precipitation minus evaporation. Units are cubic meters per second.

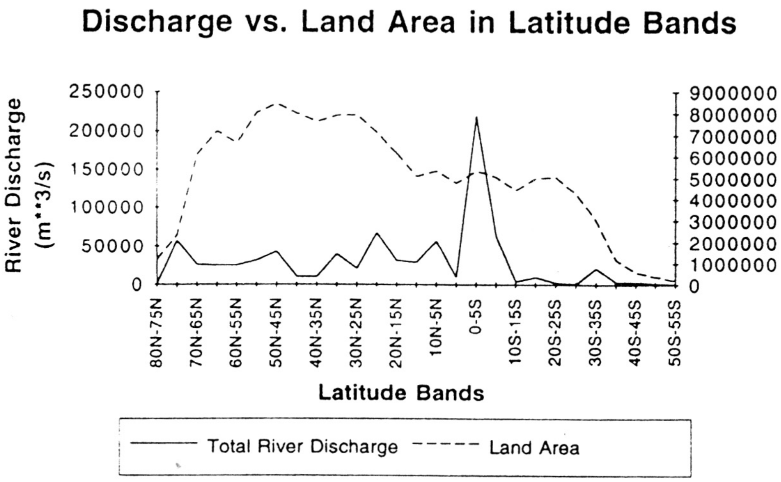

Figure 4. Total river discharge from the data set as a function of latitude. Each point represents 5 degrees of latitude. Units are cubic meters per second.

value of 1,274,950 m^3/s. The figures of [*Marcinek*, 1965, as cited by *Baumgartner and Reichel*, 1975] and *Lvovitch* [1970] (Table 4) are cited by *Baumgartner and Reichel* [1975] as upper and lower limits for global river discharge and state that a mean value of 1,213,700 m^3/s is accurate to within 5%.

Significant uncertainties are possible in these estimates. Both precipitation and evaporation vary widely over small regions, making it necessary to have a large number of measurements for an accurate estimation. At the same time, however, available physical measurements of precipitation and evaporation are sparse. Remote measurements of precipitation from satellites and Doppler radar are becoming available, but are not yet sufficient for continental-scale estimates.

Despite the uncertainty in estimates of *P-E* over continents, it seems clear that our data set is missing a significant fraction of the total runoff from continents to the oceans. The total river discharge in our data set comprises only 65% of the mean value (1,274,950 m^3/s) of contemporary estimates in Table 4, and 68% of the value (1,213,700 m^3/s) used by *Baumgartner and Reichel* [1975]. This is similar to what was found by *Nace* [1970], who estimated *P-E* over continents and compiled a list of river discharges similar to, but less extensive than, ours; he found that the sum of his measured rivers was about 70% of his estimated continental *P-E*. The issue of accounting for the other 30% or 35% of the total runoff now arises.

Factors contributing to the runoff missing from our data set include soil moisture which enters the ocean under ground, rivers which were omitted from our data set, and the fact, noted above, that discharge values in out data set are systematically low because many flow measurements are made significantly upstream from the ocean.

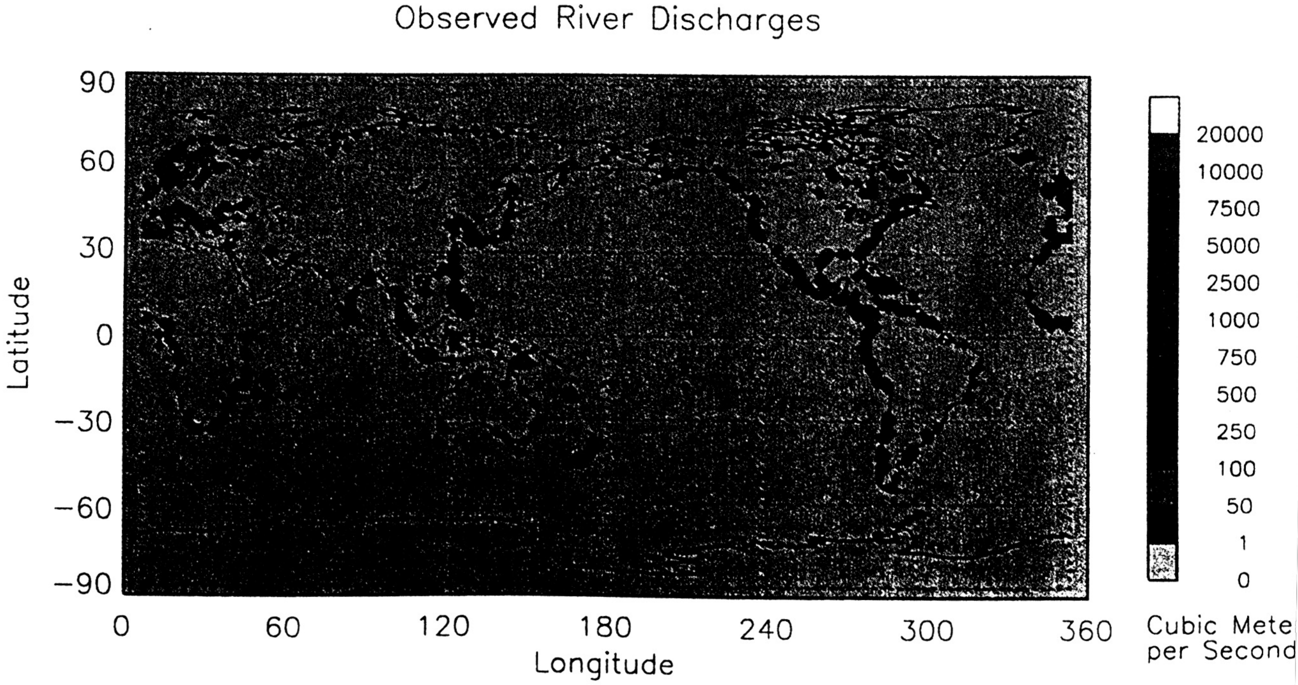

Plate 1. World map showing locations and magnitudes (cubic meters per second) of discharges from our data set.

Table 4. Data Set Discharge as a Fraction of Global Land Runoff Estimates

Source	Global Land Surface Runoff, m^3/s	Data Set as Fraction of Runoff
Brikner [1905]*	807000	1.022
Frizche [1906]*	973100	0.847
Wust [1920]*	1182000	0.698
Meinardus [1934]*	1186800	0.695
Wust [1936]*	1177300	0.700
Lvovitch [1945]*	1158300	0.712
Budyko [1956]*	1205700	0.684
Albrecht [1961]*	1063300	0.775
Budyko [1963]**	1457700/1521000	0.566/0.542
Lvovitch [1964]*	1182000	0.698
Mira Atlas [1964]**	1140800	0.723
Marcinek [1965]**	1156600	0.713
Sellers [1965]	1463700	0.563
Nace [1967b]***	1205000	0.684
Lvovitch [1970]	1273900	0.647
Mather [1970]**	1172500	0.703
Lvovitch [1973]***	1185900	0.695
Baumgartner and Reichel [1975]	1267500	0.650
Mean of entries published after [1945]	1274950	0.647

* as cited by Lvovitch [1970]
** as cited by Baumgartner and Reichel [1975]
*** as cited by van der Leeden [1975]

Despite the trivial contribution of smaller rivers to the total runoff in our data set (Figure 3), small rivers omitted from our data set may account for most of the difference between the *P-E* estimates cited above and the total runoff in our data set. This would be true if rivers with flow rates less than 250 m^3/s obey the same power-law size distribution as larger rivers. As plotted in Figure 5 (i.e., on a log-log scale), the size distribution of rivers in our data set is linear for a significant range of river sizes. (Thus rivers in this size range obey a power law size distribution.) For rivers smaller than about 250 m^3/s, however, about where one would expect the data set to start becoming seriously incomplete, the number of included rivers falls below this linear trend. We can estimate the total flux from rivers smaller than 250 m^3/s if we assume that these rivers obey the same power law size distribution as larger rivers. This is done by fitting a straight line to the linear part of the size distribution shown in Figure 5. This line obeys the equation:

$$\log_{10} N = 4.514 - 0.8419 \log_{10} Q \qquad (3)$$

where N is the number of rivers with flow rates larger than Q m^3/s. (N can also be thought of as the size-ordered "rank" of each river in the data set.) To estimate the combined discharge from small rivers omitted from our data set, we assume that (3) describes the true size distribution of rivers with flow rates less than 250 m^3/s (roughly where the observed size

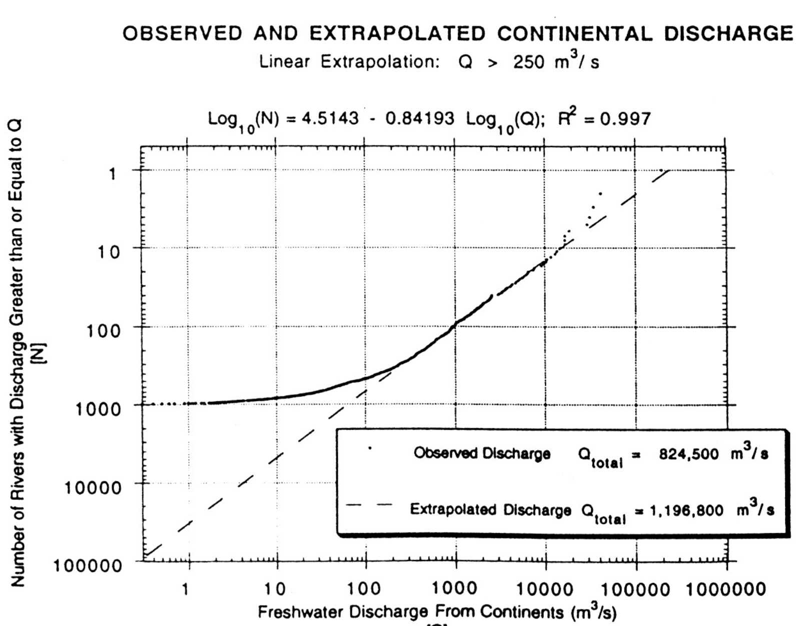

Figure 5. The observed and extrapolated size distributions of river flows in our data set. The number of rivers with flow rates (cubic meters per second) greater than Q is shown as a function of Q. Points represent rivers in our data set; the straight line is fit to the points and is used to estimate the combined flow from small rivers missing from the data set.

distribution ceases to be a power law). We estimate the total discharge from rivers with flow rates greater than 250 m^3/s by summing the observed discharges given in our data set (i.e., we assume our data set is complete for rivers with flow rates greater than 250 m^3/s). Using this approach, the estimated total runoff Q_{total} from all rivers is given by:

$$Q_{total} = \sum_{i=1}^{N^*} Q_{obs}^i + \int_0^{Q_{max}} Q \frac{dN}{dQ} dQ \qquad (4)$$

where the first term on the right-hand side represents rivers with flow rates greater than 250 m^3/s, and the second term represents the contribution from smaller rivers, whose size distribution is assumed to obey a power law. This term is evaluated by substituting (3) into (4) and evaluating (4) using Q_{max} = 250 m^3/s. This gives us an estimated total flux of 416,648 m^3/s from rivers with runoff less than 250 m^3/s. Combining this with an observed discharge of 780,154 m^3/s for rivers larger than 250 m^3/s (obtained by evaluating from our data set the summation term in (4)), we obtain an estimated total discharge for all rivers of 1,196,802 m^3/s. This is about 94% of the mean *P-E* value (1,274,950 m^3/s) cited above.

To account for groundwater flowing into the ocean underground, we use the estimate of *Lvovitch* [1970] that 5% of the total discharge is deposited to the oceans in this manner. This amounts to about 59,840 m^3/s for our data set. Adding this amount to our estimate of global river discharge gives us a final estimated value of 1,256,641 m^3/s global flux of fresh water to the oceans. This is 98.6% of the mean *P-E* value (1,274,950 m^3/s) obtained from Table 4, and 103.5% of the mean value (1,213,700 m^3/s) used by *Baumgartner and Reichel* [1975].

Thus if we assume the power law size distribution observed for rivers larger than 250 m^3/s applies to smaller rivers as well, then observed river discharges (including an estimate of underground discharges) agree with estimates of continental precipitation minus continental evaporation to within a few percent. This is clearly less than the combined uncertainties in the observed discharges and in the *P-E* estimates. Hence our data set allows for a self-consistent budget of water over continents. While we have no a priori reason for assuming that rivers smaller than 250 m^3/s obey the same size distribution as larger rivers, we have no reason to believe they do not; the fact that this assumption produces a self-consistent water budget suggests that the assumption may actually be correct.

5. Conclusions

We present a data set of observed annual mean outflows for 981 rivers. This is an order of magnitude larger than any other data set of this type that we are aware of. The data set was constructed by selectively combining previously published measurements. Care was taken to obtain flow measurements as close as possible to the oceans. For rivers with more than one published flow measurement, our data set lists the mean and standard deviation of selected measurements. Multiple reports of the same flow rate and outlying values are eliminated. Our data set appears to be reasonably complete for rivers with annual mean discharges greater than 250 m^3/s, except in the region of Oceania. The total discharge of all rivers in the data set is 824,502 m^3/s, which is about 65% of the mean of contemporary estimates of surface discharge (1,274,950 m^3/s) derived from estimates of precipitation and evaporation (*P-E*).

Rivers in our data set with annual mean discharges between about 250 m^3/s and 10,000 m^3/s obey a power law size distribution, to a very good approximation. Extending the observed size distribution to smaller rivers, and including an existing estimate of underground flow to the oceans, we obtain a total estimated flow from continents to the ocean of 1,256,640 m^3/s, which is within 1.5% of the mean *P-E* estimate. Thus within previously recognized uncertainties, and assuming our extrapolation of the observed size distribution for rivers is correct, our data set allows a self-consistent water budget over continents.

Appendix: Sources Used to Compile Data Set

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9, Dynesius and Nilsson, 1994;
10, Esser and Kohlmaier, 1991;
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13, Instituto Geografico Nacional de Guatemala, 1976;
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15, Kammerer, 1989b;
16, Kempe et al., 1991;
17, Leopold, 1962;
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19, L'Office del Recherche Scientifique et Technique Outre-Mer (ORSTOM), 1979;
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47, United States Geological Survey, Water Resources Division in cooperation with the California Department of Water Resources, 1971;
48, van der Leeden, 1975;
49, van der Leeden et al., 1990.

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